

Fifth Semiannual Report

A STUDY OF THE ELECTROTRANSPORT IN THIN FILMS

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## INTRODUCTION

This report starts with a paper which Dr. Hummel gave in June in Marstrand (Sweden) at the "Europhysics Conference" on "Atomic Transport in Solids and Liquids." It will be published in the Proceedings of the Marstrand Conference and in Zeitschrift für Metallkunde. The second paper of this report was written by two graduate students of our department (Mr. H. M. Breitling and Mr. G. L. Hofman). It was published in Proc. IEEE, 58 (1970) 833.

OBSERVATIONS ON ELECTROTRANSPORT IN THIN  
ALUMINUM FILMS USING RESISTANCE MEASUREMENTS

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Abstract

Resistance measurements of five different portions of uncoated and partially SiO<sub>2</sub>-overcoated aluminum stripes are reported. In specimens of both types the resistance increases at the cathode when the stripe is subjected to high current densities. In partially coated specimens the resistance decreases at the anode whereas it remains constant in the uncoated sample. The difference in behavior at the anode between coated and uncoated specimens is interpreted as being due to differences of ion accumulation: In the uncoated films hillocks are formed whereas in the specimen with partial overcoat the ions accumulate more evenly. Scanning-electron micrographs are shown to support this interpretation.

Observations on Electrotransport in Thin  
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Introduction

Electromigration phenomena in thin metallic films have recently received considerable attention mainly because they are a potential cause of failure of integrated circuit metallization. Another reason for the interest in electrotransport in thin films is that basic studies can be extended to much higher current densities without producing large joule heating. It is widely assumed that mass transport in thin films under the influence of a d.c. electric field is mainly governed by grain-boundary diffusion<sup>(1-5)</sup>. This concept has recently received substantial support. When the film consists of a single crystal, no measurable ion movement is observed within the experimental period<sup>(3)</sup>. When large-grained stripes are subjected to high current densities the lifetime is longer than for fine-grained samples<sup>(4)</sup>. In polycrystalline films, positive gradients of temperature<sup>(6,7)</sup>, of electron flow<sup>(6)</sup>, of current density<sup>(6)</sup>, or of grain size<sup>(4)</sup> are assumed to be the main causes of the breakdown of a film. Temperature- and current-density gradients are usually produced by the sample geometry. It must be emphasized, however, that failures were also observed to occur in regions where the macroscopic temperature is constant<sup>(4)</sup>.

Experimental evidence exists<sup>(5)</sup> to support the theory that in the early stage of electromigration, ions are transported along the stripe, whereas in the final stage growth of visible voids and catastrophic failure occur. In aluminum, holes form whenever the electrons flow in a direction of increasing temperature, i.e., predominantly at the cathode, whereas growths (hillocks and whiskers) are created where the electrons flow in a direction of decreasing temperature, i.e., predominantly at the anode<sup>(8-12)</sup>. (In thin silver films, holes form predominantly at the anode and cause the film to fail on this side<sup>(13)</sup>.) It seems, however, to be necessary to consider that void and hillock formation are not necessarily interconnected, since hillocks are also observed to form in the absence of an electric field; for example, when the temperature of the film is simply increased<sup>(14-16)</sup>. These thermal growths are believed to form because of the different thermal expansion coefficients of film and substrate. The hillocks grow on materials which are under compressive stress.

Investigations of ion movement in thin films under the influence of a d.c. electric field are generally performed employing optical-, electron-, and scanning-electron-microscopy. Resistance measurements have the advantage that structural changes in the film are noticeable well before voids can be observed visually. In some investigations the overall resistance of a thin-film stripe was measured when an electric field was applied<sup>(5,17)</sup>. This type of measurement is not well suited for detailed studies, however, because it averages the effects of all local disturbances. In order to obtain information about the changes in various regions along a stripe, it is therefore advantageous to attach to the stripe thin potential probes and to measure the individual resistance of each region. Several possible sample designs have been described<sup>(18)</sup>. The present paper discusses some recent findings which were obtained using this improved technique.

### Experimental Procedure

Thin film samples were made by depositing 99.999 per cent pure aluminum from tungsten filaments through chemically milled masks on glass substrates at room temperature in high vacuum ( $10^{-6}$  Torr). The rate of deposition was approximately 50 angstroms per second, and the distance between source and substrate was 20 cm. The silver electrodes were evaporated from a tungsten boat. Silver of 99.999 per cent purity was used and was deposited at a rate of approximately 100 angstroms per second. Silicon monoxide (purity 99.999%) was evaporated in high vacuum from a baffled chimney tantalum source.

As described elsewhere<sup>(18)</sup> the specimens consisted of a central gage section of aluminum between two partially overlapping silver electrodes. Potential leads allowed measurement of the resistance in five different portions of the sample. During the electrotransport experiment the specimen was placed in a styrofoam container in order to avoid temperature fluctuations. A temperature reading was taken with a small thermocouple on the substrate near the middle of the sample. The temperature at the center of the specimen was about 10 degrees higher than the temperature read on the substrate

### Results and Discussion

In Fig. 1, typical resistance changes in five different areas of an aluminum stripe, and the temperature reading on the sample, are plotted versus time. The positive temperature gradient in area II (cathode) promotes nucleation of vacancies and growth of voids. As a result, the resistance in this area increases substantially with time until a fuse-type effect causes the specimen to fail after about 14 hours. The resistance in the other areas changes only very little if at all when the temperature

increase is taken into consideration. It is concluded therefore that the ions which are removed from their initial positions by momentum exchange are likely to be deposited in a manner such that they give no contribution to the conductivity. In area IV (anode) especially one would expect that material is accumulated because of the negative temperature gradient. As mentioned in the introduction and as can be seen from Fig. 2, the ions pile up in the form of isolated hillocks; this is why they do not contribute to electrical conduction.

In another series of experiments, a silicon monoxide layer was deposited on a small portion near the center of the aluminum stripes. Figures 3 and 4 show the curves of resistance versus time for samples of this type. These curves represent specimens subjected to various current densities.

The partial  $\text{SiO}_2$ -overcoat causes the resistance in area IV (and later also in area III) to drop considerably. The average lifetimes of the specimens were enhanced by a factor of 10 compared to uncoated samples. (The experiment with the specimen of Fig. 3 was terminated prior to failure.) One possible explanation for the resistance drop in areas IV and III is that in these regions material is deposited in a way which increases the overall cross-sectional area of the stripe. This would suggest that no or only a few hillocks are formed here. Scanning-electron micrographs of partially coated samples support this assumption. In Fig. 5, no hillock-type growths can be seen neither in the coated nor in the uncoated area. The number of disk-shaped accumulations, however, has increased compared to uncoated stripes (Fig. 2).

The effect of a dielectric overcoat on aluminum films has been studied also by other investigators<sup>(6,19)</sup>. The dielectrics used by these authors were amorphous mixtures of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  or mixtures of  $\text{SiO}_2$  and  $\text{P}_2\text{O}_5$ <sup>(19)</sup>.

Occasionally  $\text{SiO}_2$  was used<sup>(6)</sup>. The difference between these earlier studies and the present work, however, is that the previous investigators coated the entire stripe whereas in the present work only a small portion was coated. Black<sup>(6)</sup> observed a longer lifetime of his specimens and calculated a higher activation energy for electromigration for coated aluminum films of  $12000\text{\AA}$  thickness with an  $\text{SiO}_2$  film. He attributed this to a reduction of surface- and grain-boundary-diffusion and to a filling of broken electron bonds at the aluminum surface. Spitzer and Schwartz<sup>(19)</sup> also found longer lifetimes of thin coated aluminum films (up to  $5000\text{\AA}$  thickness) when the temperature was kept relatively low. These authors emphasize that the alumina-silicate glass could reduce thermal gradients. Our observations probably fit better into the latter argument. Another possible explanation of the suppression of hillocks is that a thin layer of dielectric material changes the surface tension of the aluminum (as oil does on water) thus preventing hillock growth. More experimental information is needed for a decision between these possible explanations.

#### Acknowledgments

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## FIGURE CAPTIONS

Figure 1 Resistance change and temperature of an aluminum sample with silver electrodes versus time.

Figure 2 Scanning electron micrographs of an aluminum sample which was subjected to a current density of  $5 \times 10^5 \text{ A/cm}^2$ .

Figure 3 Resistance change and temperature of a thin aluminum stripe which was partially coated with silicon monoxide. The current density  $j$  is  $3 \times 10^5 \text{ A/cm}^2$ .

Figure 4 Resistance change and temperature of a thin aluminum stripe which was partially coated with silicon monoxide.  $j = 4 \times 10^5 \text{ A/cm}^2$ .

Figure 5 Scanning electron micrographs of an aluminum stripe which was partially coated with silicon monoxide.  $j = 4.5 \times 10^5 \text{ A/cm}^2$ .

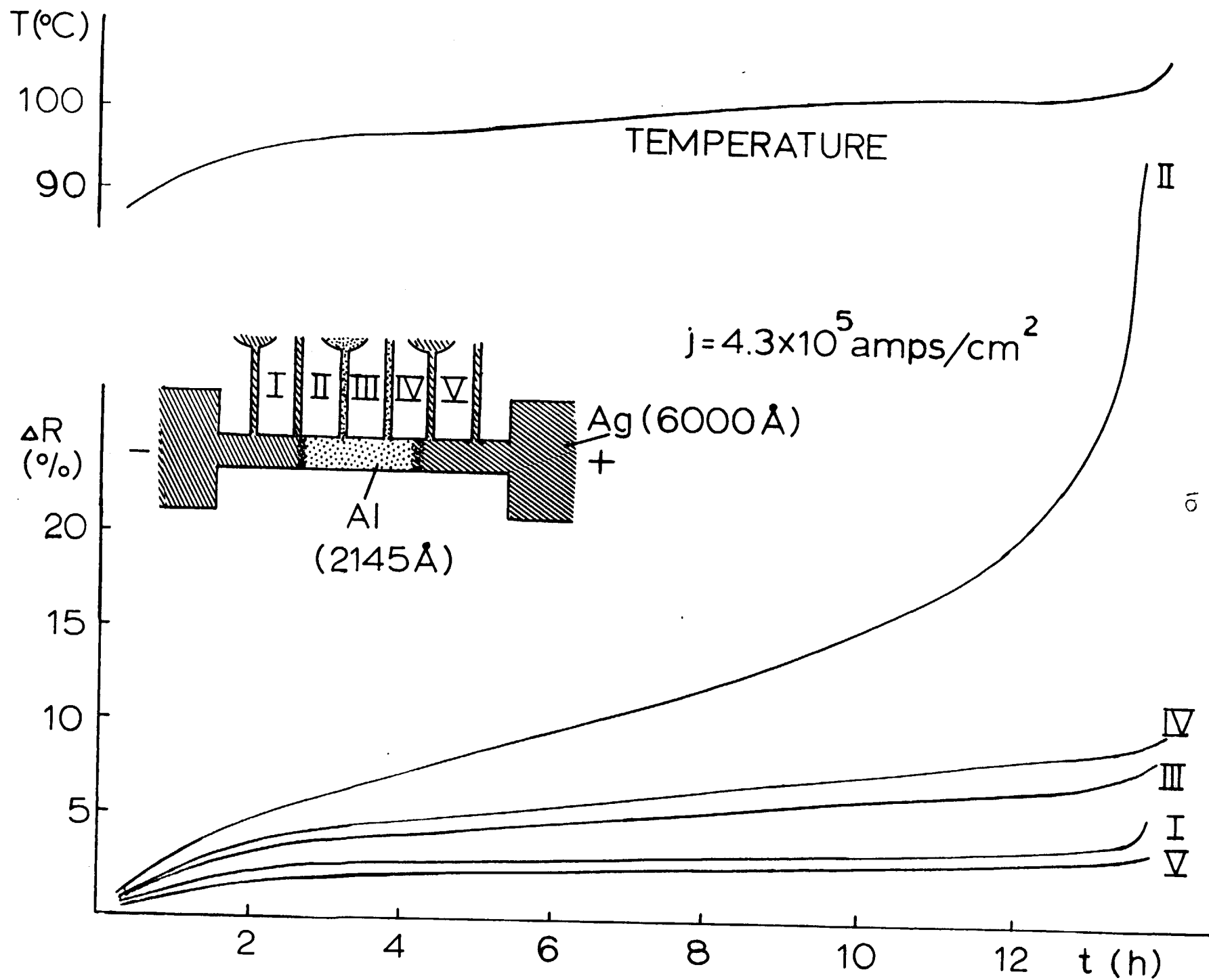
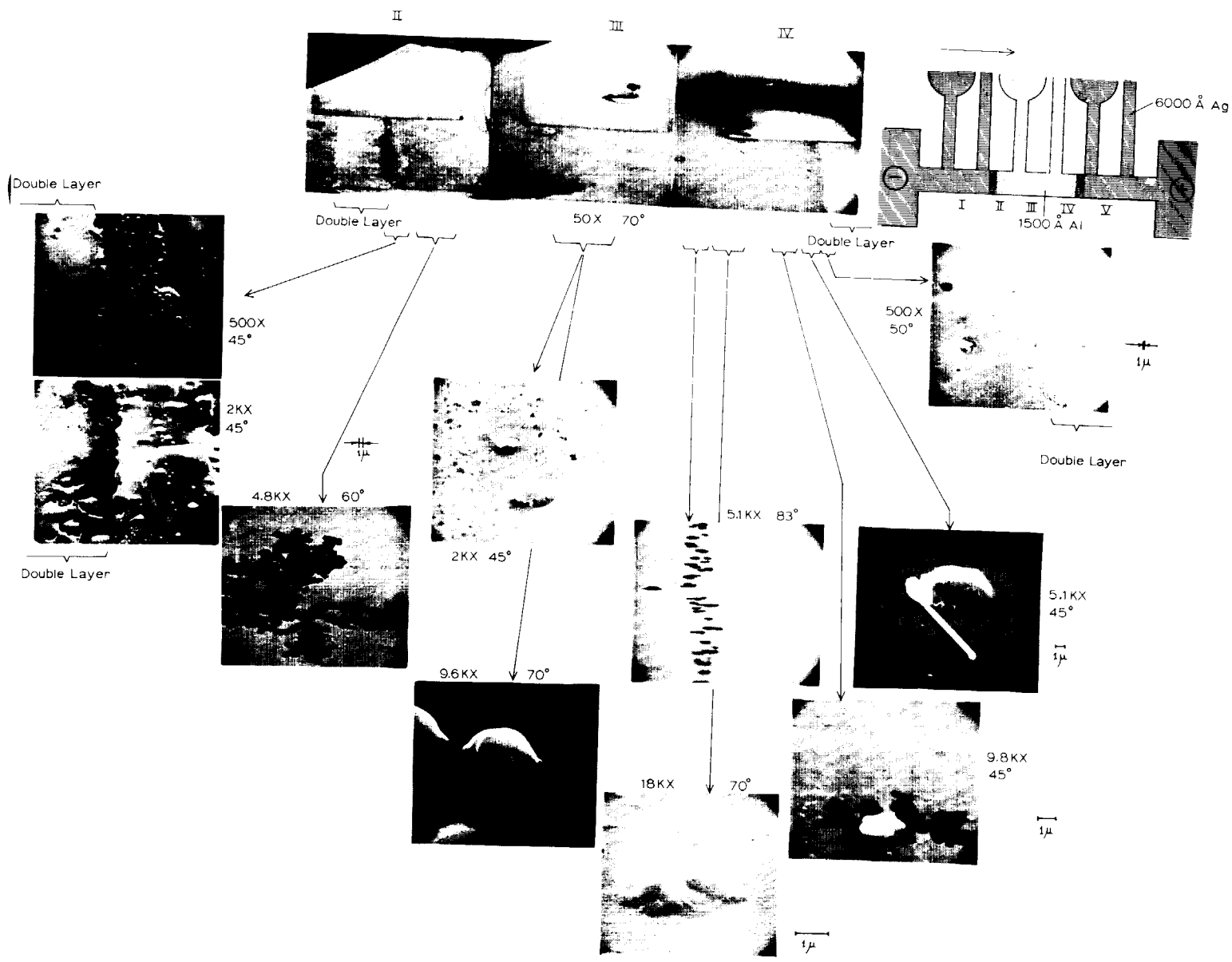


Fig. 1

fig. 2



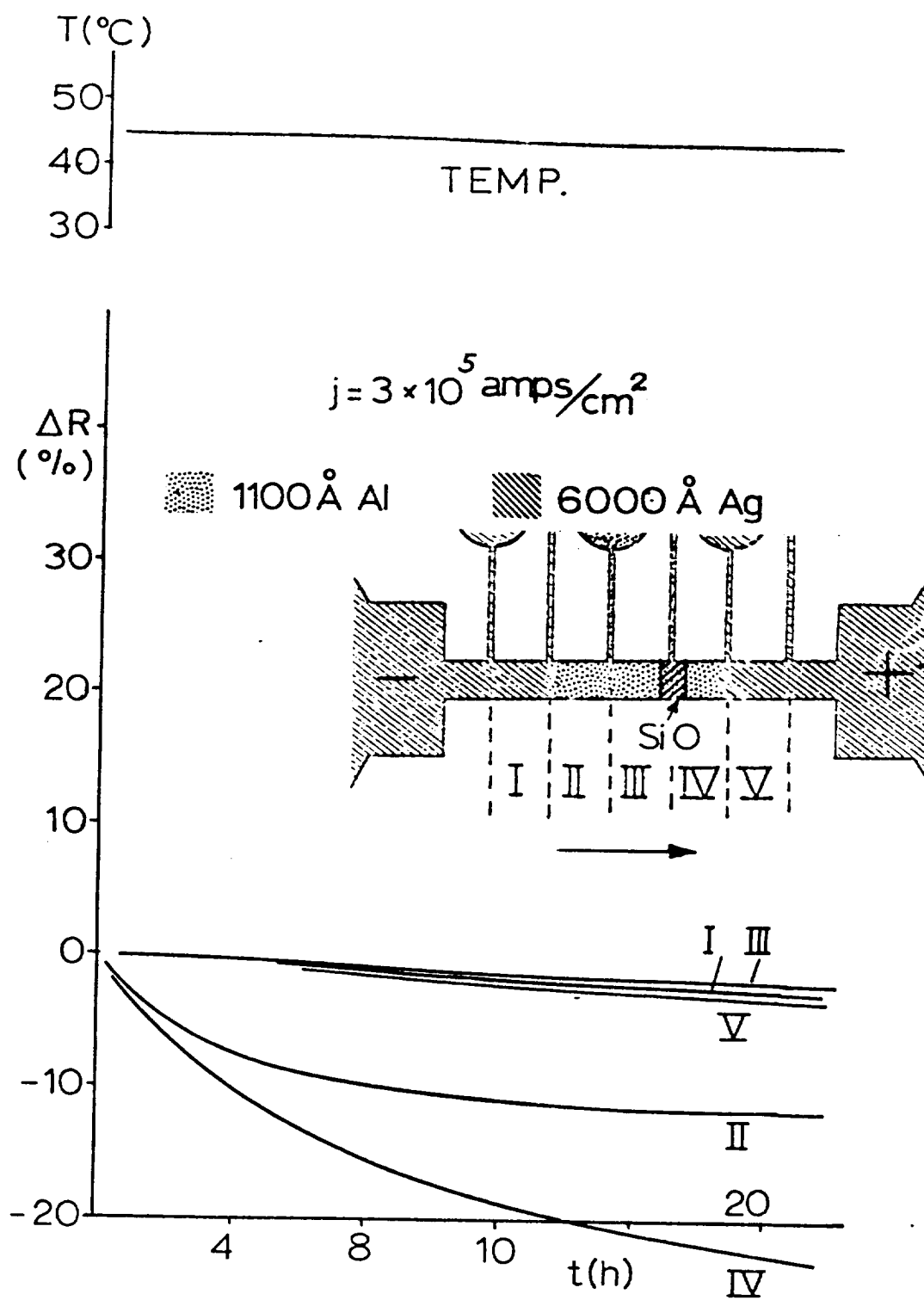


Fig. 3  
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Fig. 4  
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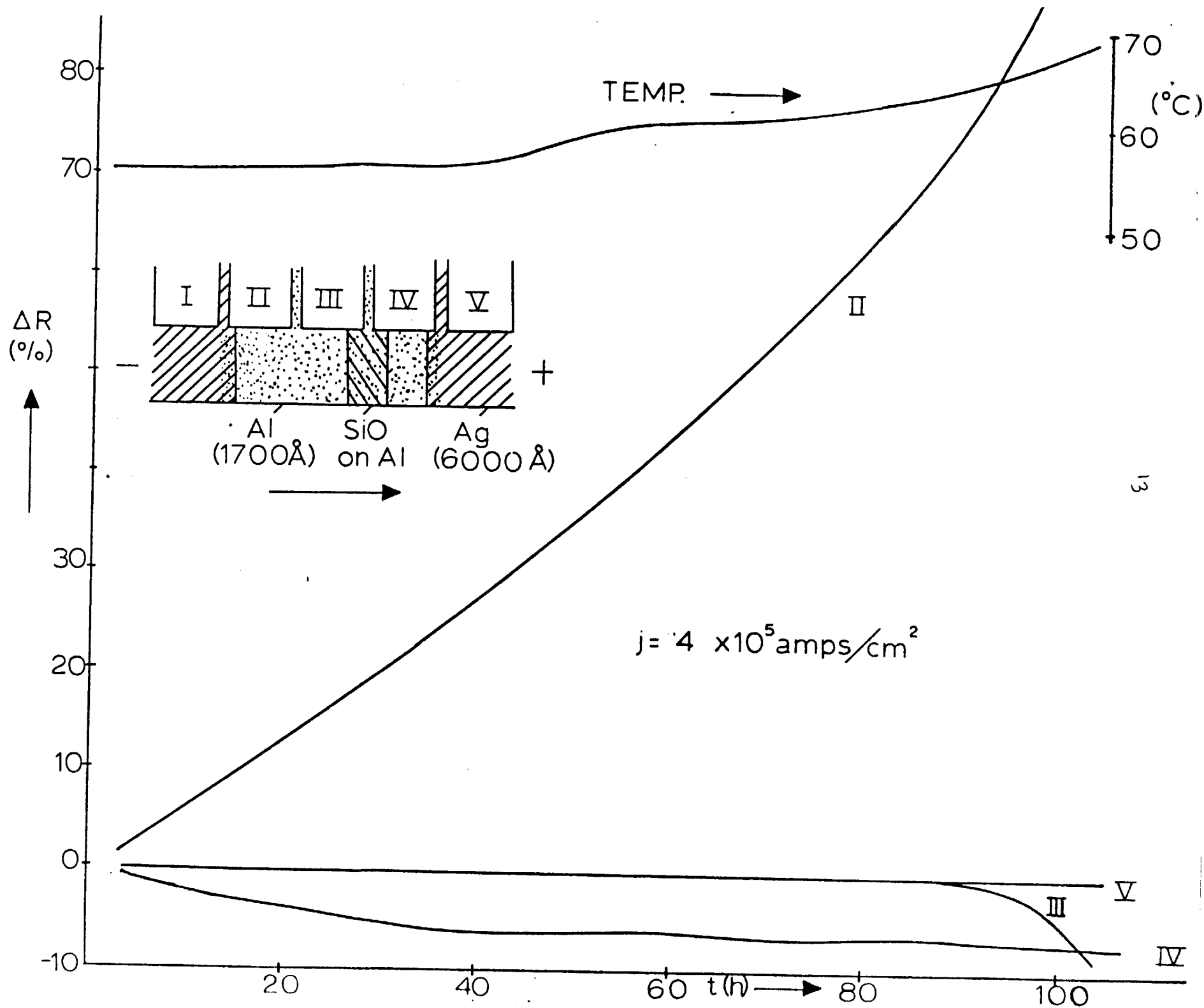
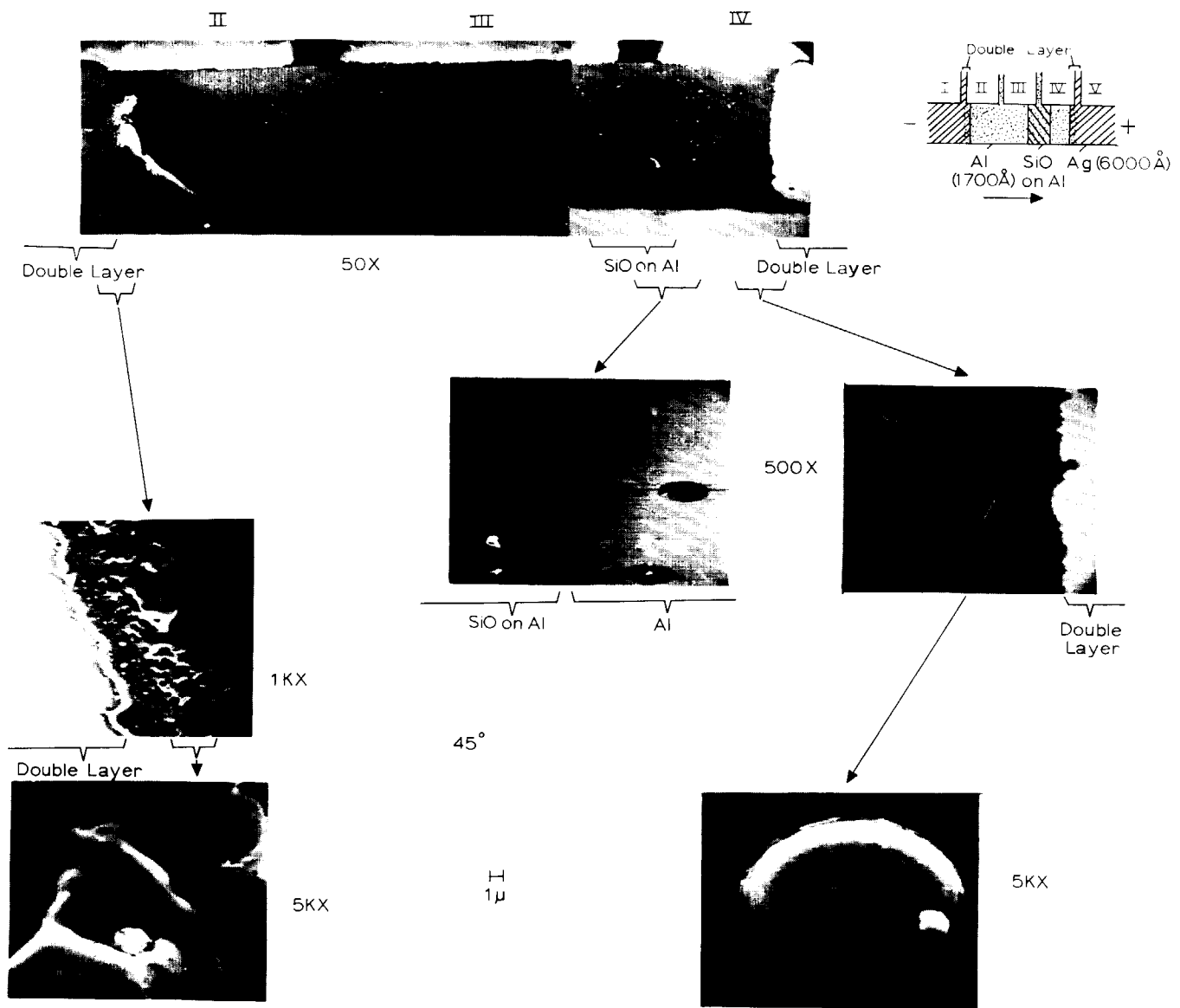


fig. 5



ON THE CURRENT DENSITY DEPENDENCE OF  
ELECTROMIGRATION IN THIN FILMS

In a recent paper in this journal<sup>(1)</sup> a theory on electromigration in metals was presented, resulting in a quadratic dependence of the rate of electromigration on current density.

Several theoretical treatments, namely by Fiks,<sup>(2)</sup> Huntington and Grone<sup>(3)</sup> and Bosvieux and Friedel,<sup>(4)</sup> all, like the presently discussed paper, based on the electron drag model, result in a linear relation between the rate of electromigration and the current density.

1) Adopting the proposition of a "simple theory", and neglecting such phenomena as the Coulomb force on the metal ions and the size effect in thin films, we come up with an expression different from that presented in<sup>(1)</sup> for the electromigration rate, and a linear relationship between electromigration rate and current density. Using the same notations as in<sup>(1)</sup> we have:

$$R = F \times (\text{average change in momentum due to } E \text{ per electron, } \langle \Delta p \rangle)$$

$$\times (\text{Number of conduction electrons colliding with the metal ions per unit volume per second})$$

$$\times (\text{Effective ion target cross section for electrons})$$

$$\times (\text{Number of activated aluminum ions per unit volume})$$

where  $R$  is the rate of mass transport and  $F$  is a constant. The average change in momentum for any conduction electron due to the applied field  $E$  is,

$$\langle \Delta p \rangle = eE \left\langle \frac{\hbar}{v} \right\rangle = eE \langle \tau \rangle \quad (2)$$



The number of electrons colliding with the metal ions per unit volume per second is given by

$$N = \alpha n_e \langle v \rangle \quad (3)$$

where  $n_e$  is the conduction electron density and  $\alpha$  a proportionality constant.

Now, if  $C(T)$  is the number of activated aluminum ions and  $\sigma_i$  the effective target cross section, we have then: (4)

$$R = F \alpha e E \langle \frac{\ell}{v} \rangle \cdot n_e \langle v \rangle \cdot \sigma_i \cdot C(T)$$

$$R = F \alpha e E \langle \ell \rangle \cdot n_e \cdot \sigma_i \cdot C(T)$$

$$R = F \alpha e \rho j \langle \ell \rangle n_e \cdot \sigma_i \cdot C(T) \quad (5)$$

or

$$R = A j C(T)$$

where  $A$  incorporates all the constants in (5). The resulting expression for  $R$  gives a linear dependence of  $R$  on  $j$ , which agrees with the theories presented in (2), (3), and (4) and not a quadratic dependence as reported in (1).

ii) It is conceded by the author in (1), that the experimental determination of the power<sup>of</sup>  $j$ , which yields 2 and appears to support his theoretical derivation, may be inaccurate because of errors in the film temperature measurements. However, no indication is given as to how large the error could be. We believe that a change in current density whether achieved by increasing the current or decreasing the film cross section may result in differences in failure history of the film, making the median time to failure method, which does not detect changes in the failure history, inaccurate in determining a  $j$  dependence.

iii) A plot of  $(wt j^{-2} \text{ MFT})$  vs  $T^{-1}$  presented in<sup>(1)</sup> gives 0.48 eV, 0.84 eV and 1.2 eV respectively for the activation energy of small crystallite, large crystallite and large crystallite glass coated films.

We agree with the argument given to explain the trend in these values. However, by plotting  $(wt j^{-1} \text{ MFT})$  vs  $T^{-1}$  we obtain for the above mentioned cases respectively 0.6 eV, 1.0 eV and 1.4 eV which fit the same argument.

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Travel Report of "Europhysics Conference"

ATOMIC TRANSPORT IN SOLIDS AND LIQUIDS

from June 15 through June 19, 1970

held in Marstrand, Sweden

by R. E. Hummel

University of Florida  
Metallurgical and Materials Engineering  
Gainesville, Florida

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Attention: Personnel Exchanges Division

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Attention Dr. I. Weinberg

General

In this conference slightly more than one hundred scientists participated and about 65 papers were presented. It was the best organized conference I ever attended. Due to the fact that the meeting took place on a small island, there were plenty of opportunities to talk to other scientists and learn about their problems or compare viewpoints. I have the impression that one meeting like this every four or five years is much more productive than semi-annual conferences in big cities.

Scientific Accomplishments

The conference covered the wide area of transport phenomena due to electrical and thermal gradients. Only three papers on electrotransport in thin films were presented, one of which was mine. The work which was done

by the Florida team drew considerable attention especially from those researchers who were not directly involved in thin film work. Dr. Wever from Berlin (Germany) wants to include some of our results in his almost completed book on transport phenomena.

The general feeling among the participants to whom I talked was that thin-film electrotransport is theroretically as well as experimentally an extremely difficult problem which is much more complex than the electrotransport in bulk materials, mainly due to the fact that thin films can no longer be considered a "one dimensional problem". It was felt that at the present time there is still a great need for phenomenological type experiments before calculations can be done. Because of the difficulties encountered some groups have already given up their research in this field.

Dr. Rosenberg from IBM Research Center (Yorktown Heights) was very careful in his statements supposedly because of pending patent applications. He agrees basically with our views and was most interested in our new findings obtained by partial overcoating the aluminum stripes.

I arranged with some of the participants that we will stay in contact for further exchange of ideas.